

Hydrodynamics and Roughness of Irregular Boundaries

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Award Number: N00014-10-1-0414

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LONG-TERM GOALS

The research goals of the work target accurate parameterization and modeling of nearshore waves, currents and turbulence in complex reef environments. A central theme of this work is the response of steady and oscillating flow to highly irregular, broad-banded roughness. Previous ONR supported study by the PI's group have quantified reef roughness, examined the hydrodynamic response to a variable roughness at small scales and explored the relationship between hydrodynamic and physical roughness.

OBJECTIVES

Specifically, the work aims to examine methods for quantifying physical roughness scales in reef environments using an autonomous underwater vehicle (AUV) and to determine the hydrodynamically relevant roughness scales for wave and current flow.

The work underway is also enabling development of a series of practical applications including examination of the relationship between measured roughness and sidescan imagery, exploration of AUV-based ADCP observations for resolution of steady flow boundary layer dynamics, and implementation of new tools for measurement of turbulent stresses in wavy environments. In addition high-resolution reef morphology data will enable further study on the correlation between roughness and other measurable reef characteristics including coral color, health and species.

APPROACH

To achieve the objectives detailed above, we are conducting a series of focused field experiments targeting resolution of flow hydrodynamics over a range of reef environments in varying wave and current conditions, with concurrent high resolution roughness mapping. The first series of observations are being carried out at the Kilo Nalu Observatory on the south shore of Oahu (Pawlak et al, 2009; www.soest.hawaii.edu/OE/KiloNalu/). A second set of observations is also being carried out in Guam in October, 2010 leveraging funding from the Army Corps of Engineers in collaboration with Mark Merrifield (UH Oceanography). A third set of field observations is targeted for the north shore of Oahu for winter, 2011.

Report Documentation Page				Form Approved OMB No. 0704-0188	
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
1. REPORT DATE 2010		2. REPORT TYPE		3. DATES COVERED 00-00-2010 to 00-00-2010	
4. TITLE AND SUBTITLE Hydrodynamics and Roughness of Irregular Boundaries				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) University of Hawaii at Manoa, Department of Ocean and Resources Engineering, 2540 Dole St., Holmes Hall 402, Honolulu, HI, 96822				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT Same as Report (SAR)	18. NUMBER OF PAGES 8	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

Observations are focused on the forereef region at each site where roughness height is small relative to the depth and wave breaking can typically be neglected. Results from this simpler domain can then provide a foundation for examining more complex roughness environments. The field experimental plan for each site features two identical bottom-mounted instrument packages, each with an upward looking 1200 KHz ADCP with 3 ADVs deployed on a nearby vertical spar, alongshore from each other and separated by roughly 200m, at depth of between 10 and 20 m. These packages target resolution of velocity profiles and Reynolds stresses. Instruments are deployed at each site for a minimum of two weeks, with longer deployments at the Oahu sites, to resolve a range of wave and current conditions.

In order to quantify the relationship between the hydrodynamic response and the physical characteristics of the reef, at each site we are carrying out high-resolution roughness surveys using a REMUS AUV equipped with a narrow beam acoustic altimeter and sidescan sonar. Surveys consist of dense ‘mow’ patterns in both along- and cross-shore directions with the vehicle operating at altitudes of 3-5 meters above the bed at depths ranging from 5 to 30 m. For the Kilo Nalu site, this covers an area of roughly 0.5 km².

We are also carrying out AUV ‘hydrodynamics’ surveys targeting the spatial evolution of current BL structure in response to the variable reef roughness. Our earlier work has shown that the REMUS ADCP can be effective in resolving steady BL structure with spatial averaging of 50-100m (Jaramillo & Pawlak, 2010a). Analysis of along-track velocities has shown evidence of weak velocity bias in the direction of platform motion in agreement with other observations from vessel and AUV-mounted ADCPs (Fong & Monismith, 2004; Fong & Jones, 2006). In Jaramillo & Pawlak (2010a), we further characterize the variability in this bias with sampling. Cross-track velocities have not shown any evidence of bias, however. Surveys thus focus on repeated cross-shore transects over the course of a tidal cycle to enable resolution of along-shore velocity profiles.

One postdoctoral researcher, Sergio Jaramillo, has been supported in part by this ONR project. The project is also providing partial support for research technicians, Kimball Millikan and Chris Colgrove, who have participated in field operations and experiment design.

WORK COMPLETED

The first year of project work has built upon capabilities developed in a previous ONR project, which enabled development of AUV sampling capabilities. Work thus far has focused on quantitative characterization of substrates and corresponding roughness in coral reef environments along with investigation of AUV capabilities for detailed hydrodynamic measurements. In addition to the standard sidescan sonar instrumentation, the UH REMUS AUV has been outfitted with a narrow-beam (2.5° beam width) altimeter with a sampling frequency of up to 18Hz, which enables resolution of small-scale bed roughness over hydrodynamically relevant scales.

Using the AUV, we have obtained measurements in the vicinity of the Kilo Nalu Observatory, at a horizontal resolution of ~5cm for sidescan backscatter data, and ~10cm for altimeter data. Compared to boat-derived roughness measurements (Nunes & Pawlak 2008), the use of an AUV for this task improves the quality and resolution of the data obtained by increasing platform stability and by maintaining a near-constant acoustic footprint for the altimeter-based roughness measurements. Methodologies for substrate characterization along with roughness characteristics for the Kilo Nalu

reef are detailed in Jaramillo & Pawlak (2010b) and are summarized below. We are presently carrying out further surveys and deployments of hydrodynamics packages at Kilo Nalu and at the Guam site.

RESULTS

AUV sidescan and altimeter data collected in the vicinity of the Kilo Nalu Observatory were analyzed to determine substrate type and roughness characteristics. The analysis of sidescan data for seabed classification uses principle component analysis (PCA) similar to that used by Preston (2009) for ship-mounted multibeam data. Several variables derived from the acoustic intensity of sidescan bottom return were examined for use in the PCA analysis. Best results were obtained using variance, skewness, entropy, power spectral slope, and anisotropy calculated on the georeferenced sidescan data. These variables were calculated in boxes of 6m by 6m, without overlap, covering the complete acoustic data domain.

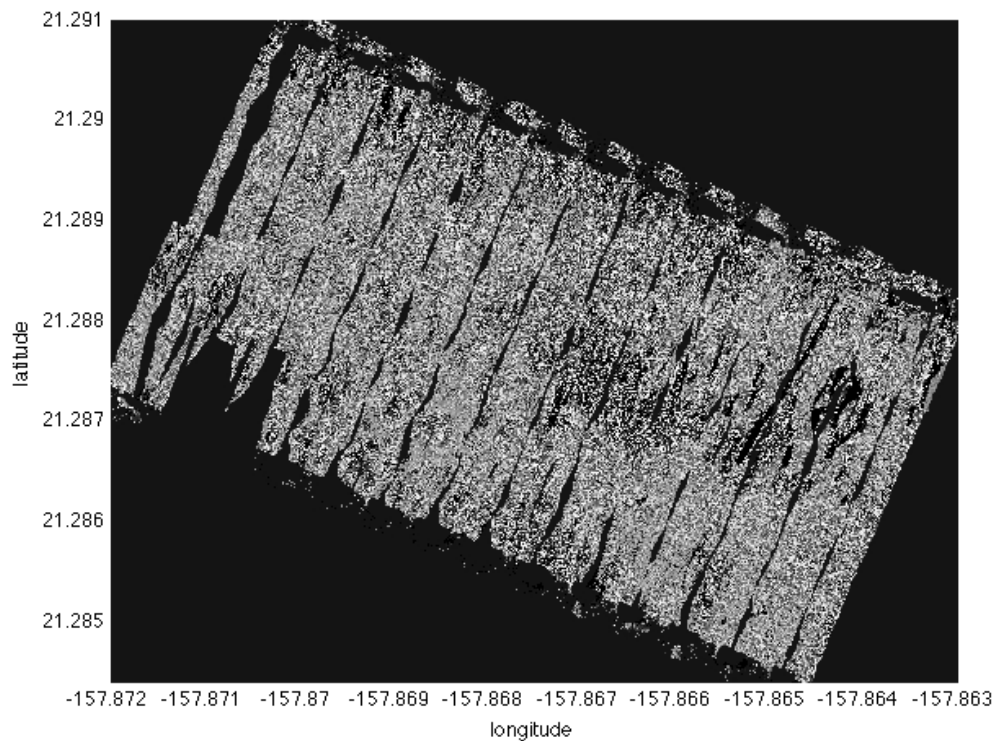


Figure 1 Mosaic image of sidescan backscatter collected in the KNO vicinity.

To identify different bottom types near Kilo Nalu, we use the PCA results to reduce the sidescan backscatter information to essentially two statistical modes (PC1 and PC2) that account for 74% of the total variance (Figure 2). The spatial patterns for PC1 and PC2 reflect the spatial patterns of sand, coral, and sand ripples observed over the surveyed area. Visual verification of these similarities indicates that, using this technique for automatic detection of seabed type, we can separate these bottom classes with a degree of certainty that varies according to the choice of a PC threshold value. In our case, we set this threshold value to $PC1 > 1$ for coral (80% accuracy), $PC1 < -0.6$ for sand (75% accuracy), and $PC2 < -2$ for sand ripples (75% accuracy). The spatial distribution of bottom type corresponding to these thresholds is shown in Figure 3. A similar, but more comprehensive approach has been used in the past to discriminate bottom types using multi-beam echo sounder data (Preston

2009) although not at the high resolution we present here. Due to the simplicity of the methodology, these techniques could be easily applied elsewhere given the wider availability and economy of sidescan sonar systems over multi-beam echo sounders.

Although the validity in using spectral estimates alone for characterizing broad-banded roughness is questionable because phase information is lost (i.e. different signals can have similar power spectra, Rajagopalan 2010), the RMS roughness is still a robust estimate of the energy content within a given wavenumber band. While the altimeter-derived bottom range spectra over the study area did not reveal any conspicuous length scales, using the sidescan-based bottom classification we are able to assign estimates of physical roughness to the sand and coral areas using mean RMS values of 3.3cm and 7.3cm, respectively, calculated within the 0.2 – 6 m⁻¹ roughness band. Figure 4 shows the relationship between PC1 magnitude and RMS altitude within this band. The highest RMS values over the survey area correspond to coral covered areas found in the shallower (<10m) part of the surveyed area, consistent with findings by Nunes and Pawlak (2008).

Ongoing efforts are being directed to the identification of hydrodynamically relevant length scales for flow over coral reefs. The RMS roughness values measured during this study are an initial step in that direction.

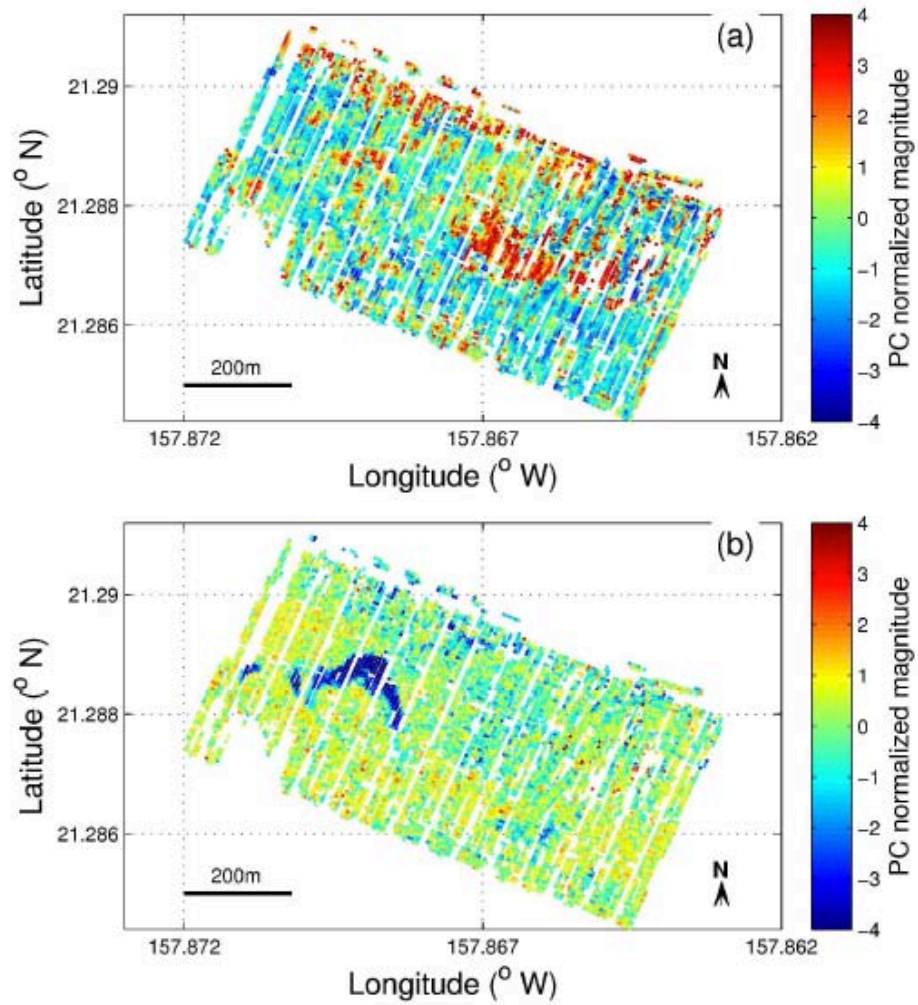


Figure 2) Spatial distribution of sidescan-derived PC coefficients. a) PC1 coefficients (51% of variance); b) PC2 coefficients (23% of variance).

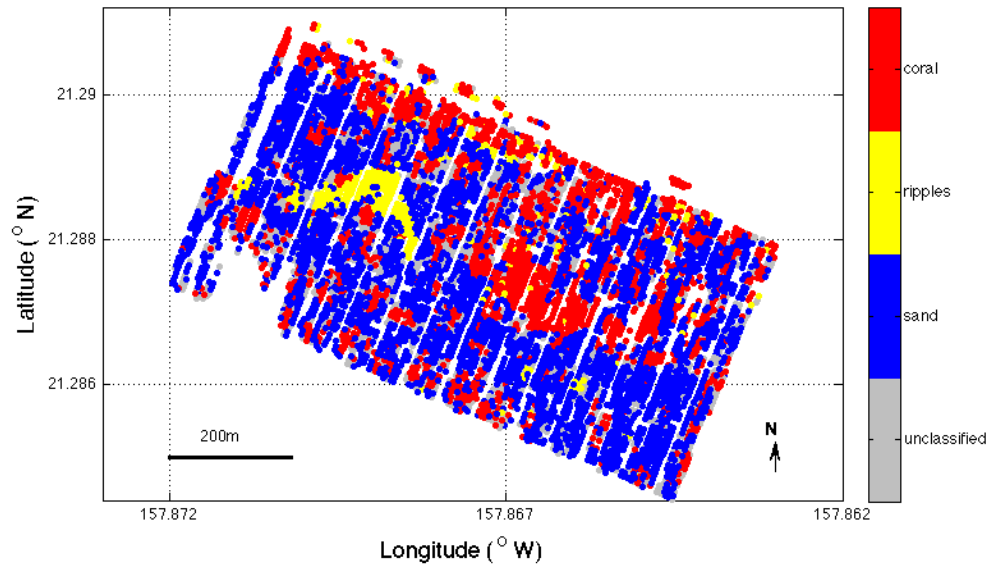
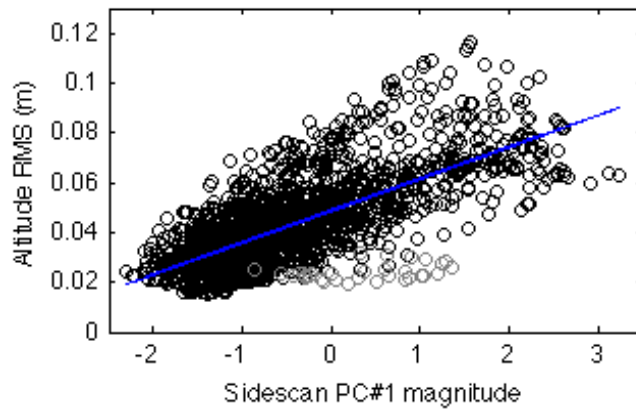


Figure 3) PCA-based classification of seabed types near the Kilo Nalu Observatory.



**Figure 4) Comparison between RMS altitude and sidescan PC1 magnitude for KN survey data.
Linear fit of sidescan PC1 magnitude to RMS altitude gives $R^2=0.51$.**

Analysis has also continued on extensive data sets collected as part of earlier ONR-funded work examining the near-bed structure of flow over highly rough bathymetry. The observations include data from deployments of the Rough Boundary Profiler (RBP) which employs a downward looking ADCP, profiling horizontally over a stretch of reef to generate a two-dimensional, phase-averaged velocity field over a 2m (cross-shore) x 1m (vertical) plane, as a function of wave-orbital amplitude.

IMPACT/APPLICATIONS

Coral reefs are a dominant feature of coastal environments at low latitudes. Effective littoral operations in reef environments require accurate prediction and modeling of wave and current dynamics over complex boundaries as well as characterization of acoustic and optical processes. Turbulent processes at the seabed are at the foundation of littoral hydrodynamics with the bed shear stress as a key parameter affecting dissipative and dispersive mechanisms.

In addition to direct effects on nearshore hydrodynamics, turbulence over rough beds influences optical and acoustic properties. Bed roughness also directly affects acoustic propagation in the coastal zone. The observations described here will enable more general characterization of bed morphologies in reef zones and will establish foundation for remote sensing of bed characteristics from aerial and satellite imagery. Beyond applications in coral reefs, the research is extending understanding of hydrodynamics of flow over complex boundaries in general.

The work described above has enabled new research applications focusing on benthic roughness mapping and classification, which have implications for nearshore wave and current modeling. Combined with direct measurements of roughness from a narrow-beam altimeter recently added to the UH AUV, sidescan imagery can provide valuable 2D context, enabling substrate identification and classification in complex reef environments. These observations can potentially be correlated with remote sensing methods to provide benthic classification with more extensive spatial coverage.

The detailed analysis of AUV DVL performance, underway as part of the ongoing work, is critical for development of AUV-based spatial hydrodynamic sampling. AUV spatial surveys can, in turn, provide a key tool for assessment and characterization of nearshore processes on complex coastlines.

Finally, the ongoing work is making use of the cabled Kilo Nalu Observatory baseline infrastructure. Kilo Nalu has enabled real-time access to data, facilitating deployment of instruments that would otherwise be limited to short-term deployments. The initial Kilo Nalu infrastructure was deployed largely with support of earlier ONR grant, and was further developed with support from an NSF Coastal Ocean Processes (CoOP) project.

RELATED PROJECTS

The work discussed here has been directly motivated by results from earlier ONR funded projects including a Young Investigator grant that focused on wave boundary layer dynamics (see data in figures 1 and 2) and led to the establishment of the Kilo Nalu Observatory. Further ONR support has focused on internal tide effects on currents at Kilo Nalu. The REMUS AUV was acquired via an ONR DURIP. S. Jaramillo has also been supported as a postdoc via an ONR grant to develop AUV capabilities at Kilo Nalu. Ongoing NSF-funded projects at Kilo Nalu are focused on wave and current boundary layer turbulence in the context of benthic geochemical exchange and stratified turbulence.

A USACE funded project (PI: Merrifield) targeting wave transformation and coastal flooding for island shorelines includes AUV-based roughness surveys at Guam, is enabling extension of the work described here providing an additional data set for analysis.

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PUBLICATIONS

The following publications have been produced under support of this project.

Jaramillo, S. and G. Pawlak, AUV-based bed-roughness mapping over a tropical reef, *Coral Reefs*, submitted, September 2010.

Jaramillo S. and G. Pawlak, AUV-based observations of rough bed hydrodynamics, *Proceedings IEEE AUV2010 Conference*, Monterey, September 2010